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Flat plate collector for process heat with full surface aluminium absorber, vacuum super insulation and front foil

Thomas Beikircher^a, Peter Osgyan^a, Manfred Reuss, Gloria Streib^{a*}

^aZAE Bayern e. V., Walther-Meissner-Str. 6, Garching 85748, Germany

Abstract

A new flat plate collector is under development for economic process heat of temperatures between 80 ° and 150 °C. A vacuum super insulation (VSI) with micro-porous powders (perlite or fumed silica) in an evacuated (0.1 mbar) stainless steel envelope has been developed for the rear side of the collector which replaces the mineral wool insulation of standard collectors. CFD simulations of the equivalent thermal conductivity of the VSI including losses via the powder and edge losses have been performed depending on geometry. Applying a 100 µm thin VA foil as VSI cover, the collector losses can be reduced by about 0.6 W/m²K. Between glass cover and absorber the collector will be equipped with a transparent ETFE foil reducing the loss coefficient further by about 1.2 W/m²K. Additionally, a full surface aluminium absorber with a very high collector efficiency factor F' of 0.97 is used, reaching maximum collector efficiencies of about 0.9. Up to a temperature difference of 110 K, the new collector is estimated to have higher efficiencies than standard flat plate and vacuum tube collectors. In the temperature range of 80 ° and 150 °C the efficiency is expected to lie between 65 % and 35 %. Four different and successively improved prototypes are under test and construction, respectively. The first prototype showed the principal feasibility of the concept and was the first VSI collector operated under outdoor conditions at temperatures up to 120 K over ambient.

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Keywords: Flat plate collector, process heat, vacuum super insulation, perlite, fumed silica, edge losses, equivalent thermal conductivity, full surface absorber, highly transparent front foil insulation, ETFE-, FEP-film

* Corresponding author. Tel.: +49-89-329-442-58 ; fax: +49-89-329-442-23 .

E-mail address: streib@muc.zae-bayern.de

1. Introduction

To fulfill the CO₂-reduction targets, thermal collectors are needed not only for low temperatures (solar domestic hot water), but also for process heat with temperatures at medium level between 80 ° and 150 °C. Currently there are various attempts to develop such new collectors, e. g. for the food and clothing industry as well as for solar cooling.

Nomenclature

| | | | |
|-----------|---|----------------------|---|
| a_1 | first order heat loss coefficient | <i>Greek symbols</i> | |
| a_2 | second order heat loss coefficient | α | heat transfer coefficient |
| A | surface area of insulation | η_0 | optical efficiency |
| d | insulation thickness | λ | thermal conductivity |
| F' | collector efficiency factor | τ | transmittance |
| L | insulation perimeter | ψ | linear thermal transmittance / porosity |
| p | pressure | ρ | density |
| \dot{q} | leakage rate | | |
| T | temperature | <i>Subscripts</i> | |
| U | thermal transmittance / heat loss coefficient | A | ambient |
| | | equ | equivalent |
| | | F | fluid |

To reach higher temperatures, lower collector losses have to be realized without significantly raising production costs. This has not been accomplished so far. In today's standard flat plate collectors, the losses comprise of front losses which are between 3-4 W/m²K and rear losses of about 1 W/m²K. Due to imperfect heat transfer between absorber and fluid, the absorber temperature lies significantly over the fluid temperature and collector efficiency factors F' of 0.9 are typical. This leads to additional losses. With full surface absorbers F' can approach 1 and eliminate these overheat losses nearly completely. Hence, instead of maximum collector efficiencies of $\eta = 0.85$, up to about $\eta = 0.9$ can be reached [1].

For the rear side losses, mineral wool or polyurethane foam is used as thermal insulation which have a thermal conductivity between 0.03 and 0.06 W/mK during normal operation and in dry state. The currently most often used mineral wool absorbs water from the air during service. Hereby, the thermal conductivity can rise from 0.05 W/mK to the 20-fold value in the worst case scenario [2]. The new collector avoids this problem by using a vacuum super insulation and reduces the overall losses to produce high temperatures.

Apart from the glass cover, in most current flat plate collectors, there are no measures taken to reduce the front losses. They comprise mainly of convection (about 2.5 W/m²K) and radiation (about 0.5 W/m²K). Possible efficient solutions for their suppression available in market products are FEP/ETFE foils or structures like honeycombs that act as convection barriers. Under development are transparent insulations like monolithic aerogel or a second low-e coated glass cover. In this work, an ETFE foil will be used.

The focus of this project is to improve both front and rear insulation of the collector as well as heat transfer between absorber and fluid.

2. Full surface aluminium absorber

In the early days of solar collectors there has been an attempt to use full surface aluminium absorbers like roll-bond absorbers. In those days, the great potential could not be realized satisfactorily due to material problems like corrosion. Recently, these concepts are resumed with different absorber types. One of them is an absorber of a Finnish company. The absorber comprises of twelve stripes that are brazed into a header pipe at the top and bottom, see Fig. 1. (a). It is available in two variants. The first has nine small tubes on the rear side of the absorber parallel to

the stripes, see Fig. 1. (b) on the left side. The second variant consists of a multi-port extrusion (MPE) profile. 38 rectangular flow channels of about 2 x 1 mm form an absorber stripe, see Fig. 1. (b) on the right side.

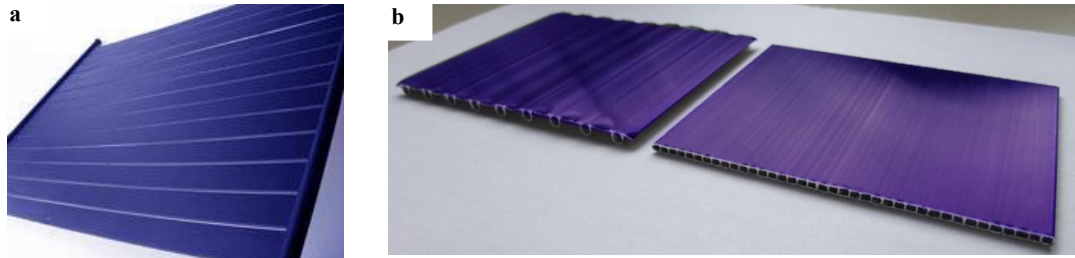


Fig. 1. (a) Full surface aluminium absorber with profiles brazed into header tubes [9]; (b) Absorber profiles.

As the heat transfer between metal and solar fluid is very good due to direct-flow the collector efficiency factor F' has a very high value of up to 0.97. In combination with an AR-coated glass cover this leads to an extraordinary high optical efficiency (0.896) of the collector [1].

Furthermore, this full surface absorber has a newly developed MEMO coating which consists of three thin ceramic layers based on Si, Al and Ti ($\alpha = 0.96$). These layers are deposited by PVD and PECVD technology, in an in-line coating vacuum machine. The production is cost efficient and the recyclability is improved compared to absorbers with a mixture of aluminium and copper.

3. Vacuum super insulation

3.1. Principle, properties and applications

Apart from completely evacuated flat plate collectors, the rear losses seldomly have been addressed in an innovative way until now. The idea behind any insulation is to use a porous or fibrous material with air enclosures. The gas in the pores or gaps of the material is hindered to move to a great extent due to friction of the gas on the pore walls and the small dimensions of the hollow spaces. Therefore, no convection occurs. Air at rest has a thermal conductivity of $\lambda = 0.026$ W/mK. All thermal conductivities in this text are given for room temperature and dry condition, unless otherwise stated. The smaller the pores are, the better the value of air can be approached with a non-evacuated insulation material. Nevertheless, the skeletal structure of the material adds solid heat conduction to the total thermal conductivity which results in higher values compared to air at rest. Besides convection and gas heat transfer, radiation is suppressed in an insulation by absorption and isotropic reemission within the material.

High quality PU foam has a very low thermal conductivity of 0.025 W/mK, whereas mineral wool shows about 0.04 W/mK. Thermal conductivities are temperature dependent. In contrast to building applications, temperatures for solar collectors vary significantly. Therefore, it has to be carefully examined, for which temperatures thermal conductivities are given.

To go below these thermal conductivities, a vacuum insulation like in vacuum flasks can be used. Applying high vacuum, gas conduction can be completely suppressed and solid body conduction only occurs at the small junction areas of the vacuum confining walls. However, radiation is not avoided. To minimize this kind of heat loss, a micro-porous filling material can be applied (vacuum super insulation, VSI). Due to the micro-pores, a moderate vacuum (typically 0.1-10 mbar depending on the filling material) is sufficient to eliminate gas heat conduction. Total thermal conductivities amount to very low values of 0.003-0.008 W/mK.

Vacuum super insulation is already used for storage of cold liquid gases such as nitrogen, argon or helium. Other applications are vacuum insulation panels (VIPs) which are used for building insulation or vacuum insulating sandwich elements (VIS) used e. g. in refrigerated storage rooms [3]. In contrast to those products, the use of a VSI in solar collectors requires its applicability with respect to high temperatures. VIPs for example can only tolerate temperatures up to 70 °C. Apart from the vacuum tightness this is a quite challenging aspect of this project.

3.2. VSI filling material for the collector

A literature research revealed that in principal four materials are usable as super insulating filling material for the collector, namely expanded perlite, fumed silica, glass fibres and aerogel. They are mainly based on SiO_2 . Their thermal conductivity as a function of air vacuum pressure can be seen in Fig. 2. Aerogel is the best insulator in the whole pressure range. Unfortunately, its very high price excludes it from the use in a collector. Fumed silica is the second favorable powder as it has a very low thermal conductivity beginning from $\lambda = 0.004 \text{ W/mK}$ for pressures lower than 6 mbar and only $\lambda = 0.02 \text{ W/mK}$ at ambient pressure. With a density of $\rho = 280 \text{ kg/m}^3$ it would lead to a very high collector weight. Furthermore, the price exceeds the acceptable costs for a collector application. The problem with weight and costs applies for the glass fibres as well.

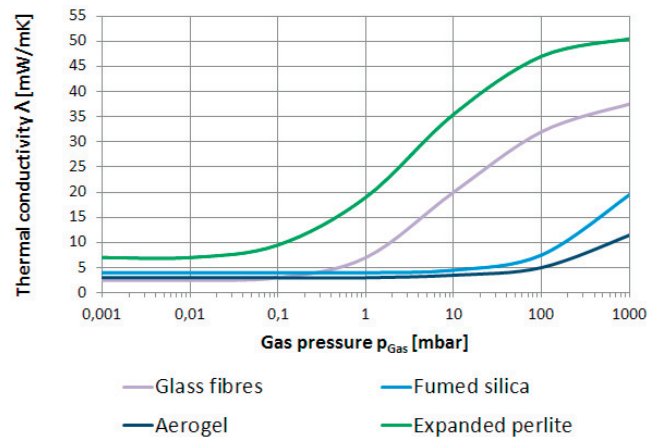


Fig. 2. Thermal conductivity of VSI material for the collector as a function of gas pressure [3,4].

Consequently, the expanded perlite (SiO_2 , Al_2O_3) was chosen as the suitable material for the VSI, see Fig. 3 (a). It is a volcanic glass (obsidian) and is transformed in an expansion process under temperatures of 800-1000 °C to 15-20 times its original volume. The material softens and the contained water evaporates which builds pores in its internal structure. A porosity of $\Psi = 0.75$ -0.97 results, see Fig. 3 (b). The grain size varies between different types of perlite. The expanded perlite in this VSI collector, “Technoperl C 1,5” by Europerl Inc., is normally used for cryogenic applications and has a grain size maximum of 1.5 mm. 50 % of the grains lie between 0.125 and 0.5 mm [4]. The thermal conductivity starts from 0.007 W/mK for pressures lower than 0.05 mbar and goes up to 0.05 W/mK for ambient pressure. Although this is high compared to the other VSI filling materials, it is acceptable at pressures below 0.1 mbar. With a vacuum tight envelope (leakage rate $\dot{q} = 1 \cdot 10^{-8} \text{ mbar} \cdot \text{l/s}$) and, if necessary, the use of a getter this vacuum level can be achieved over a lifetime of 20 years. Furthermore, perlite is very cheap (50 €/m³) which results in only 4 € for a collector with an aperture area of 2 m² and a standard 40 mm insulation thickness. Compared to mineral wool with about 6-8 € this is quite good.

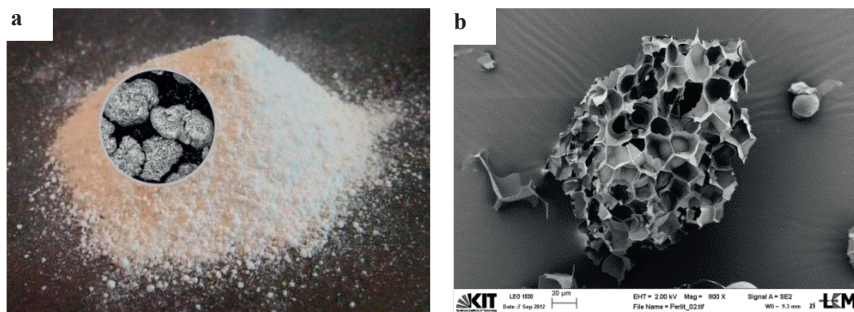


Fig. 3. (a) Photo of expanded perlite and SEM of the grains; (b) SEM of inner structure of expanded perlite.

3.3. Thermal bridge effect

The very low thermal transmittance due to the evacuated filling material unfortunately is only part of the total U-value of the insulation. The relatively high thermal conductivity of the metal confinement consisting of VSI sheet and casing (stainless steel with $\lambda = 15 \text{ W/mK}$) leads to a thermal bridge effect which influences the insulation value. The equivalent thermal conductivity λ_{equ} of the VSI combines the powder value λ_{powder} with the one from the casing λ_{casing} [5]:

$$\lambda_{equ} = \lambda_{powder} + \lambda_{casing} = \lambda_{powder} + \Psi \cdot \frac{d \cdot L}{A} \quad (1)$$

Here, Ψ is the linear thermal transmittance of the confinement, d the insulation thickness, L the perimeter of the insulation confinement and A the top surface.

Unfortunately, the metallized plastic films used for VIPs cannot be applied for the VSI collector as the PE/PET does not withstand the high temperatures of the collector during operation. Furthermore, the transmission rate of water vapour and gas molecules through the film is an exponential function of temperature. This is not relevant for building applications as only temperatures up to 50°C occur. But with long service at high temperatures in the collector this would lead to a drastic increase in vacuum pressure which reduces the thermal insulating effect to an unacceptable value. Therefore, a stainless steel foil has to be used like in VIS elements where it is chosen for stability reasons.

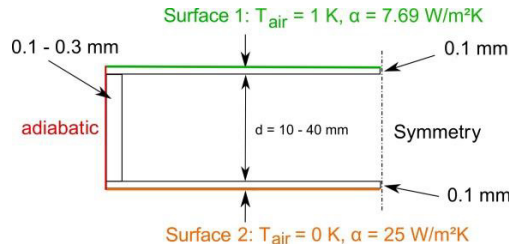


Fig. 4. Names and boundary conditions of the model in [5]

Numerical simulations on thermal bridge effects of VIS can be found in [5]. Ψ is calculated from the results of the simulation for panel thicknesses between 10 and 40 mm and sheet thicknesses at the envelope sides (membrane) between 0.1 and 0.3 mm, see Fig. 4. As the geometries and thicknesses investigated are not comparable to the collector geometry a CFD simulation was done with Ansys CFX and Mechanical APDL. To check the validity of the model, the configuration “Variation 2” in [5] was simulated. Thereby, it could be found that in [5] there was a mistake in the final calculation of the thermal transmittances which the authors could verify. The correct values can be seen in Table 1 which are a factor 2 lower compared to [5].

Table 1. Linear thermal transmittance Ψ [W/mK] calculated with Ansys CFX according to the model in [5] for four different panel thicknesses d_{VIS} (10-40 mm) and three different sheet thicknesses at the envelope side $d_{membrane}$ (0.1-0.3 mm). The top and bottom surface has always a thickness of 0.1 mm.

| | $d_{membrane}$ [mm] | | |
|----------------|---------------------|-------|-------|
| d_{VIS} [mm] | 0.1 | 0.2 | 0.3 |
| 10 | 0.044 | 0.053 | 0.057 |
| 20 | 0.035 | 0.046 | 0.052 |
| 30 | 0.028 | 0.040 | 0.046 |
| 40 | 0.024 | 0.035 | 0.042 |

With the validated numerical model, the collector geometry was used and different boundary conditions, valid for the collector case, were applied. Due to symmetry reasons, only a fourth of the collector was modeled. The dimensions were 1020 x 620 x 40 mm with 345.600 nodes. For the heat transfer between absorber and top surface of the VSI sheet a heat transfer coefficient of $\alpha_t = 2 \text{ W/m}^2\text{K}$ was applied. In the first VSI collector prototype (Case 1 in Table 2) the absorber lay on the VSI sheet and therefore the heat transfer coefficient had to be adapted. It was set to $\alpha_t = 9 \text{ W/m}^2\text{K}$. For the transfer between casing and surroundings α_c was set to $20 \text{ W/m}^2\text{K}$ [6], see Fig. 5. The thermal conductivities of the stainless steel casing and the perlite powder were temperature dependent. The air temperature above the top surface was 160°C and the ambient temperature 30°C .

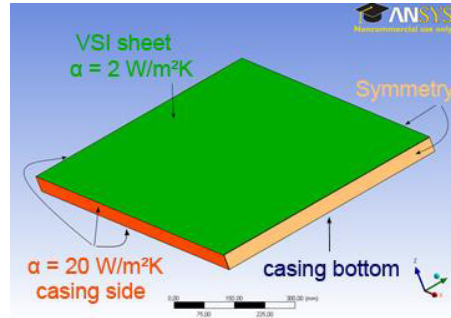


Fig. 5. Ansys CFX model of the VSI insulation of the flat plate collector with applied boundary conditions

To calculate the linear thermal transmittance Ψ , the total heat input onto the VSI sheet \dot{Q}_{VSI} was read from the results obtained by the numerical simulation, taking into account that only a fourth of the geometry was simulated. Furthermore, the heat input onto the top powder surface \dot{Q}_{powder} was determined, which describes the heat loss by the pure powder insulation. Subtracting these two expressions results in the heat that flows over the collector side-casing. To obtain Ψ this value is divided by the difference of the air temperatures above the VSI sheet and under the casing bottom ΔT and the perimeter of the collector L :

$$\Psi = \frac{\dot{Q}_{VSI} - \dot{Q}_{powder}}{\Delta T \cdot L} \quad (2)$$

Table 2. Linear thermal transmittance Ψ [W/mK] for a 2040 x 1040 x 40 mm VSI in a flat plate collector calculated with Ansys CFX (Case 1-5) and Mechanical APDL (Case 6), respectively. The thermal conductivities of the stainless steel casing and the perlite powder (evacuated, $p = 0.05 \text{ mbar}$) have been calculated temperature dependent. The resulting λ_{casing} and the total heat loss \dot{Q} of the insulation are given. The different thicknesses of the VSI confinement have been labeled as follows: 0.1/0.6/0.8 e. g. would be a 0.1 mm VSI sheet, a 0.6 mm casing side and a 0.8 mm casing bottom. Case 1 describes the first prototype ($\alpha_t = 9 \text{ W/m}^2\text{K}$), Case 2 the second prototype ($\alpha_t = 2 \text{ W/m}^2\text{K}$). The casing side thickness in Case 1 of 1.6 mm is due to the fact, that the VSI sheet actually was a tub mounted up-side-down to guarantee easy laser welding. Cases 3-6 show the effect of different configurations in cover thicknesses.

| Model | Ψ [W/mK] | λ_{casing} [W/mK] | \dot{Q} [W] |
|-----------------------|---------------|---------------------------|---------------|
| Case 1: 0.8/1.6/0.8 | 0.221 | 0.0229 | 275 |
| Case 2: 0.1/0.8/0.8 | 0.046 | 0.0048 | 117 |
| Case 3: 0.1/0.6/0.6 | 0.045 | 0.0047 | 116 |
| Case 4: 0.1/0.8/0.1 | 0.046 | 0.0048 | 117 |
| Case 5: 0.1/0.1/0.1 | 0.038 | 0.0039 | 111 |
| Case 6: 0.025/0.8/0.8 | 0.023 | 0.0024 | 99 |

The results of the simulation are summarized in Table 2. The VSI sheet has the largest impact on the thermal bridge effect and therefore a very thin sheet should be used. The variation of the casing thickness has a minor influence. A VSI sheet with a thickness of 0.025 mm would improve the insulation properties, but the difference to the 0.1 mm sheet is not very large. Such a thin VA film of 25 μm has not been available in a width of 1000 mm which is necessary for the collector. Therefore for the second prototype (Case 2) a 0.1 mm sheet was used. The equivalent thermal conductivity of the VSI is $\lambda_{\text{equ}} = 0.0151 \text{ W/mK}$ for a perlite mean temperature of $T = 90 \text{ }^\circ\text{C}$ and a vacuum pressure of $p = 0.05 \text{ mbar}$. This results in a heat loss of $U = 0.38 \text{ W/m}^2\text{K}$ compared to $1 \text{ W/m}^2\text{K}$ for a mineral wool insulation.

3.4. VSI collector prototypes

The first prototype of a VSI insulated solar thermal collector with dimensions 2000 x 1200 x 90 mm was built with a 0.8 mm stainless steel casing and a VA sheet of the same material covering the vacuum insulation on top. A laser weld joined the casing with the sheet. Expanded perlite was filled into the resulting vacuum chamber and was evacuated using a vacuum pump. A pressure of $p = 0.01 \text{ mbar}$ could be reached. A meander absorber and an anti-reflective coated glass cover were used. The collector efficiency was measured at the outdoor test facility of the ZAE Bayern. The efficiency was comparable to standard collectors and could not be improved with this first prototype.

A second prototype with dimensions 2000 x 1000 x 90 mm was built with a thin stainless steel sheet of only 0.1 mm glued to the 0.8 mm casing, see Fig. 6. (a) and (b). As the seam quality concerning vacuum tightness could not completely be estimated beforehand, it was filled with fumed silica powder. In contrast to expanded perlite, fumed silica keeps lowest thermal conductivity of $\lambda = 0.004 \text{ W/mK}$ for pressures up to 6 mbar. A possible high leakage rate of the vacuum space should therefore not alter the good insulation properties. A full surface aluminium absorber was mounted in the casing. The glass cover was a structure glass with a transmittance of $\tau = 0.915$ as it could be taken from a series collector with the same dimensions. Collector efficiency results for an antireflective-coated glass can be easily calculated. Two further prototypes will follow with a laser welded seam. For joining the 0.1 mm stainless steel foil with the 0.8 mm casing, a heat conduction laser weld will be used. Tests showed the applicability of this weld for the collector assembly. The vacuum space will be filled with fumed silica in the form of plates and expanded perlite powder, respectively. In a second step, an ETFE foil will be mounted.

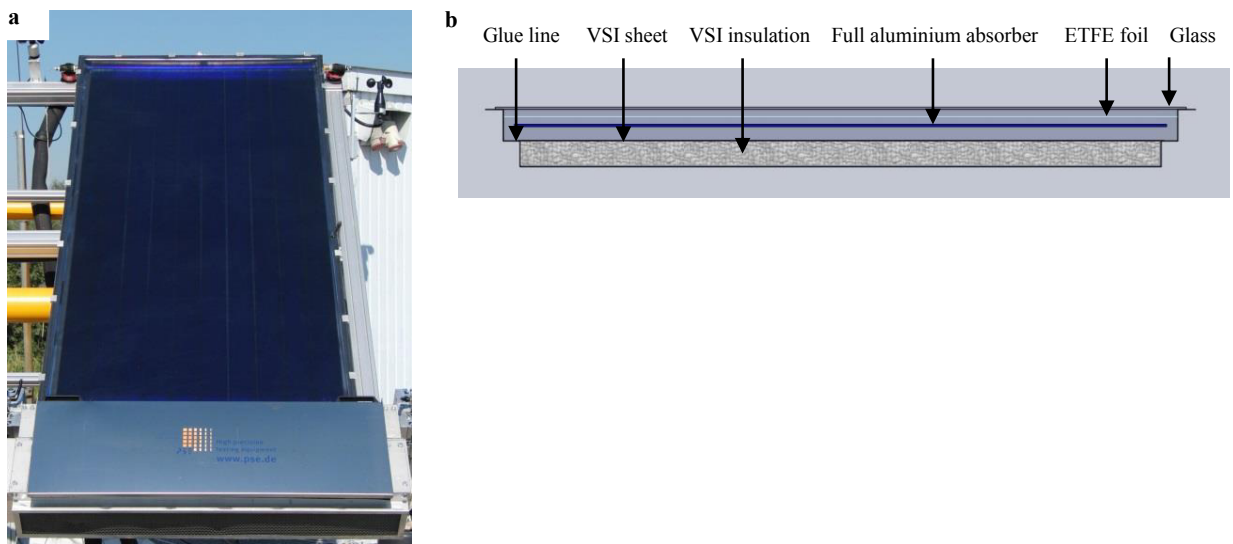


Fig. 6. (a) Second prototype of the VSI collector at the outdoor test facility of the ZAE Bayern (without foil). It has a structure glass as cover, a full surface aluminium absorber and fumed silica powder as VSI filling material. (b) CAD assembly of the VSI collector (with ETFE foil).

4. Front Foil

A front foil of highly transparent polymer can be mounted in the space between absorber and glass cover to reduce the front losses. As material ETFE (Ethylene tetrafluoroethylene) or FEP (Fluorinated ethylene propylene) can be used. ETFE has a transmittance of 0.94 whereas FEP even surpasses this value with 0.96. But as ETFE is cheaper (2.5 €/m²) compared to FEP (4.5 €/m²) for a 25 µm thickness this material will be used in the project. It is temperature stable up to 250 °C and therefore even high stagnation temperatures cause no problem. With sufficiently high tension applied during mounting no wrinkles will occur during operation [8]. For this aim it appeared best to clamp the foil on four sides in the casing, but a two side clamping is possible as well. The material is long-term stable concerning light (no degradation of transmittance), chemicals and moisture if mounted in the collector. Furthermore, it is a light material and will not contribute to collector weight like a second glass cover.

With a front foil the total loss coefficient of a flat plate collector is reduced by 1-1.5 W/m²K [7]. This has been shown experimentally at the ZAE Bayern, which developed the front foil insulation between 2007 and 2010. To not mix the different effects of VSI insulation and foil on the collector efficiency, the first tests were performed without the front foil. The effect of the improvement due to the foil can easily be estimated in good approximation by subtracting a mean value of 1.2 W/m²K from the first order heat loss coefficient a_1 in the efficiency formula. Nevertheless, a combination of VSI and foil will be tested in a next step.

5. Measurements

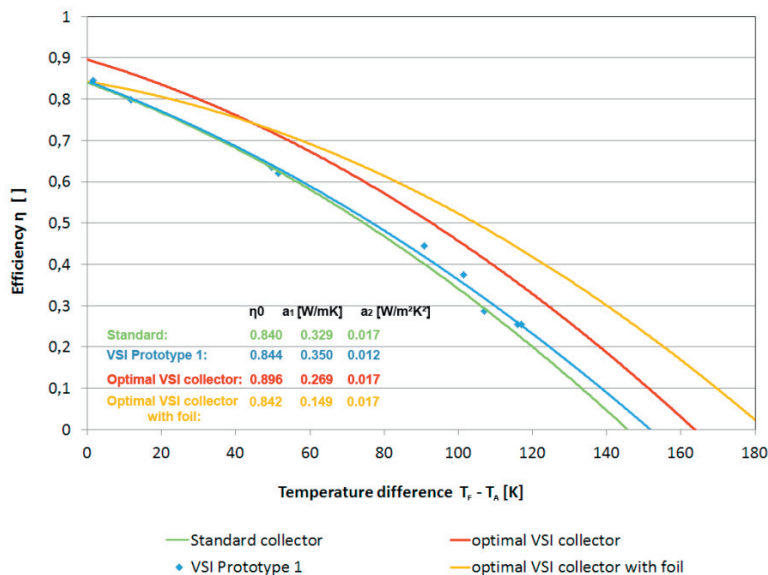


Fig. 7. Collector efficiency curves of a standard flat plate collector, the first VSI prototype and the estimated curves of the optimal VSI collector and the one enhanced with a foil as a function of temperature difference between mean fluid and ambient temperature.

The prototypes were tested on the test facility of the ZAE Bayern on a solar tracker of the company PSE. The efficiency curves, the optical efficiency and the heat loss coefficients can be seen in Fig. 7. The “optimal VSI collector” (red curve, theoretical) assumes the optical efficiency of the full surface absorber and an anti-reflective coated glass. The first order heat loss coefficient a_1 is reduced by 0.6 W/m²K due to the VSI compared to the standard collector, see Chapter 3.3. The “optimal VSI collector with foil” (yellow curve, theoretical) is obtained by multiplying the transmittance of ETFE (0.94) to the optical efficiency and further reducing the first order heat loss coefficient a_1 by 1.2 W/m²K.

The first prototype has an efficiency curve only slightly higher compared to the standard flat plate collector which was measured simultaneously on the test facility. This result was attributed to the high bridge losses of the

VSI sheet (0.8 mm). Furthermore, the absorber was lying on the VSI sheet which leads to higher losses according to the CFD simulation. To improve the efficiency and reach the estimated red curve of the “optimal VSI collector” in Fig. 7, the second prototype is under test since September 2013.

6. Conclusion

Two prototypes have been built with a VSI insulation to replace the mineral wool to reach higher temperatures for process heat. Apt filling material for the VSI and possible joining methods for the VSI sheet and the collector casing have been investigated. A CFD simulation showed the influence of the thickness of the VSI sheet on thermal bridge effects and gave advice for the design of the second prototype. Until now the efficiency could not be improved compared to a standard flat plate collector. A second prototype is under measurement and two further VSI collectors are under construction and will be measured in autumn 2013. In a next step, an ETFE foil will be mounted between glass cover and absorber to reduce the front heat losses.

Acknowledgements

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